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WYLE LABORATORIES - RESEARCH STAFF

QUARTERLY PROGRESS REPORT

FOR JANUARY, FEBRUARY AND MARCH, 1965

CONTRACT NO. 8-11308

Aerodynamic Noise Research Support

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA

Attention: PR-EC

April 9, 1965

Work during the beginning of the quarter concentrated on the production of a preliminary prediction technique for the aerodynamic pressure fluctuations on space vehicles. A draft prediction technique was prepared but it became apparent that knowledge of the phenomena was neither sufficiently complete, or sufficiently organized, to enable a properly based prediction technique to be developed. It is already possible to produce engineering figures on the fluctuating pressures, but it is necessary to employ very conservative estimates in order to afford an adequate margin over the present uncertainties in knowledge. In particular, the mean characteristics of the vehicle flow field could not be defined with sufficient accuracy.

Thus, the major effort in the second part of the quarter has been aimed at determining more closely the mean flow characteristics, particularly of the separated parts of the flow field which are the major sources of fluctuating pressure. The major problem in the interpretation of these flows is the lack of good schlieren or shadowgraph pictures of typical regions of separation. Many pictures must exist, but these are inadequately reported in the literature, and even when these are reported, the extremely poor quality of the reproductions available from the central agencies prohibits any interpretative work. In view of this, it is particularly unfortunate that shadowgraph pictures of their flow fields were not obtained during the recent tests at Ames. In order to overcome this lack of information several workers were contacted directly, and additional information acquired. This has led to an extension of the separated flow classifications presented in the first quarterly progress report of this contract. This work is not entirely complete, but the results of the work to date are discussed in Appendix A.

Additional work during the first part of the quarter involved rewriting Appendix A of the second quarterly progress report as a separate Research Report. This was submitted with the February progress report. As a result of that investigation it was decided to perform a subsidiary study of the mechanism of transition from laminar to turbulent flow in a boundary layer. This study has led to some results which are of major basic interest to transition mechanisms and these are discussed in Appendix B of this report. This study has also revealed an interesting result of relevance both to that work and to the hypothesis advanced in Wyle Research Report WR 65-2. An addendum to the report which discusses this point is included as Appendix C.

Work during the remainder of the present contract period will again concentrate on the preparation of the prediction technique for aerodynamic pressure fluctuations. The immediate task is to complete the study of the mean parameters of the separated flow discussed in Appendix A. It is hoped that a draft prediction technique can be prepared before the end of May so that this may be reviewed by MSFC for final rewriting as the end product of this contract.

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APPENDIX A

FLOW FIELDS ASSOCIATED WITH TURBULENT SUPERSONIC SEPARATION

Introduction

Since the largest sources of fluctuating pressures are the regions of turbulent supersonic separation and their associated oscillating shock waves, it is of major importance to define the mean flow characteristics of these regions. In the first quarterly progress report of this contract (Reference 1) a classification was put forward which led to a useful simplification of the separated flow problem. Investigation during the present quarter has revealed new information which extends the details of this classification.

Discussion

In Reference 1 it was shown how the well known phenomenon of bow shock attachment and detachment for supersonic flow (shown here in Figures 1a and 1b) had a parallel in the case of separated flow. Supersonic turbulent separation is normally caused in practice by a forward facing flare or step and it was shown how two types of supersonic separation existed broadly corresponding to the flare angle being greater or less than that for shock detachment (Figure 3 of Reference 1). If it is possible for a flare shock to exist then the flow pattern shown in Figure 2a will occur if the height of the flare is large enough. The mean flow parameters for this type of separation have been investigated in detail by Kuehn in Reference 2 and the results of a further analysis of his work were presented in Reference 1. The flow shown in Figure 2a is typified by a two shock pattern. The first "separation shock" is located at the beginning of the separation region and a second "flare shock" is centered on the compression corner of the flare. Reattachment for the flow shown in Figure 2a occurs on the flare, near to the compression corner.

In the second class of flows shown in Figures 2b and 2c reattachment occurs at, or near to, the shoulder so that the two classes of flows may be distinguished by their "flare reattachment" and "shoulder reattachment" respectively. Figure 2b shows the shoulder reattachment case that was discussed in Reference 1. Here attachment takes place at the shoulder expansion fan. Note that in practice an expansion fan is usually associated with a recompression shock as shown. Figure 2c shows a shoulder reattachment case that was overlooked in the discussion of Reference 1. However further review showed that this type of flow has in fact been observed in a number of experiments, for instance those of Kepler and Bogdonoff (Reference 3). Here reattachment takes place via a small highly curved shock located at the shoulder as shown in Figure 2c. An unusual feature of this shock is that it becomes almost negligibly weak, presumably due to an interaction with the shoulder expansion fan.

It appears that the flow shown in Figure 2c is typical of that over a forward facing step, whereas that of Figure 2b is usual on the more gradual flares that occur on Saturn type vehicles. This difference in flow types throws additional doubt on the validity of making vehicle environmental predictions from pressure fluctuation measurements on forward facing steps, such as those of Kistler (Reference 4) or some of the recent tests at Ames, and further work will be required to determine their validity.

In order to reach a closer understanding of those phenomena it is worthwhile to study the mechanisms of separation and reattachment in more detail. Figure 3 shows some velocity profiles and streamlines for a hypothetical case. Separation occurs at S because the slower moving fluid in the upstream boundary layer does not have sufficient energy to overcome the increase in pressure imposed by the separation shock. At the point of separation the velocity profile is as shown with a point of inflexion. The flow beyond the separation point may be divided into two parts by the separation streamline S R. Within the "separation bubble" defined by S R there is a low speed circulating flow whereas the flow outside S R reacts substantially as if S R were a solid surface. A second line of interest is that joining the zero velocity points in the separation region (shown dashed in Figure 3).

Consideration of the equilibrium of the various regions of the separated flow leads to some interesting conclusions. Firstly, consider the equilibrium of the region of negative velocity between the zero velocity line and the wall. The wall shear stress acts in the opposite direction to the local flow. In addition turbulent momentum interchange across the zero velocity line will also give rise to an effective opposing shear stress along that line. Thus the total negative momentum in this region must continually reduce as the separation point is approached from within the separation region. This is of course the practical result, but it can also be seen how the generation of the negative velocities near the reattachment point requires that a pressure gradient be present.

The requirement that the negative momentum in the separation region becomes smaller as the separation point is approached necessarily implies that the positive velocity increase away from the separation point, so that, in the absence of any other effect, the velocity along the separation streamline would continually increase. This is again intuitively obvious from a number of viewpoints but it is apparent that this velocity could not increase indefinitely since there is no mechanism by which part of the separation region could reach a higher velocity than the free stream. Thus there should be some limiting case which occurs when the local flow profiles reach a final fixed shape from which subsequent development can only be by increase of scale. In principle, calculations can be made following this idea, but in practice considerable difficulty is encountered. However this does give a more realistic physical basis for the Russian work discussed in Reference 1 so that the limiting case of 17° 42' obtained for the angle of the separation region does have some justification. A possible modification to this theory would incorporate the effect of wall shear stress on the flow. This would result in a slightly smaller, and thus more accurate result. Calculations along these lines will be made during the next quarter if time permits.

The mechanism of reattachment of the flow was explained by Chapman in Reference 5. Consider the flow profile near reattachment shown in Figure 3. Suppose the pressure at the reattachment point is p_r. The velocity profile shown implies a variation in total head across the reattachment zone. If the flow is assumed to undergo isentropic compression during reattachment then the momentum of the local flow will be transformed into pressure. Streamline "a" in Figure 3 has sufficient total head to overcome the pressure occurring at reattachment whereas streamline "b" in Figure 3 with insufficient total head is reversed back into the separated region. It can be seen that the total pressure on the dividing streamline is equal to the static pressure at the reattachment point. The Chapman concept of separation and reattachment is that the velocity increases along the dividing streamline via viscous transfer processes until it is finally converted into static pressure at the reattachment point through an isentropic compression.

This idea ignores the effect of turbulent momentum transfer near the reattachment point. In fact it is possible to conceive of cases where the turbulent interchanges will have a major effect on the flow, with energy being removed at the wall by an alternating wall velocity imposed on a nearly stagnant mean flow. This case is extremely difficult to approach theoretically, but the more moderate effects of turbulence etc., may be included in the calculation by introduction of an "efficiency of recompression" factor.

Returning now to the three cases shown in Figure 2 it is apparent that in both Figures 2a and 2c the reattachment takes place via a shock with consequent pressure rise. Note in Figure 2c how the shock near the top of the shoulder implies a sharp pressure rise at this point almost immediately followed by a rapid fall in pressure as the flow passes through the shoulder expansion fan. The conditions for separation and reattachment discussed above are satisfied throughout the flow and a satisfactory model flow can be laid down.

It is considerably more difficult to find a model separated flow which satisfies the conditions shown in Figure 2b in every particular. Reattachment occurs when the total head of the dividing streamline overcomes the static pressure at reattachment. From this viewpoint reattachment via an expansion fan with consequent lowering of static pressure is acceptable. However it will be recalled that the reversal of the flow within the separation bubble requires a pressure rise towards reattachment and this is inconsistent with the above model. The most probable solution seems to be a gradual pressure rise up the flare which accomplishes the reversal, so that the expansion fan does not play a direct part in the reattachment process. Note that in this case the efficiency of recompression factor will be low and much of the turbulent energy may be dissipated directly by the wall shear during the final stages of reattachment.

This suggestion is consistent with the observed fact that the flow of Figure 2b usually occurs on flares of moderate angle while the flow of Figure 2c occurs on "flares" with high angles such as forward facing steps. Additional evidence comes from the observation that the angle of separation observed in 2b type flows is higher than that for 2c type flows. This is shown in Figure 4 derived from the Ames test data. Here the angle of separation has been calculated by dividing the distance from the shoulder to the forward inflexion point of the pressure distribution by the height of the flare. The separation angle found for the 30° flare is as high as 16°, close to the 17° figure found for the flows of Figure 2a in Reference 1. However the flow over the 90° step (type 2c) gives effective angles near 12°.

The reason for this was observed in the shadowgraphs of Kepler and Bogdonoff (Reference 3). The highly turbulent part of the flow extended above the line to the shoulder as is shown in Figure 2c. Reattachment through the shoulder shock is a rapid process, and it can be seen that the angle of the line from the shoulder to the separation point is somewhat less than the angle of the separation. Analysis of the shock wave angles in Reference 3 showed that a typical value of the separation angle was about 14.5° although this value became smaller at lower step heights, and there was also a slight tendency to reduction at the largest step heights.

Thus it seems that in each case shown in Figure 2 the angle of separation is somewhere near 15°, but the varying method of reattachment for each type causes differences in the effective angle of the total separation region.

It is difficult to make a priori estimates of the fluctuating pressures that will be recorded in each case. Both cases 2a and 2c have shock waves at attachment, which must be expected to be moving. Certainly the motion of these shock waves is very apparent in the shadowgraphs given by Kuehn in Reference 2 for case 2a. In addition the flow for case 2c has a strong vortex in the corner which must be expected to increase the magnitude of the fluctuating pressures. The flow shown in Figure 2b does not have a reattachment shock wave, but is seems probable that there will be relatively high levels of turbulence up the flare towards the reattachment point. Thus in all cases relatively high levels of pressure fluctuation might be expected near the reattachment point.

The shadowgraphs of Reference 3 also threw some light on the mechanisms of shock oscillation. In many pictures several simultaneous distinct shockwaves could be seen, corresponding to separation angles between 12° and 17°. This presumably corresponds to the fact that the separation shock wave in front of the step was not absolutely straight across the flow. Thus at any one station it would be expected to move about within these limits of angle above.

[Clearly the first requirement of a prediction technique is to be able to decide which type of flow will exist under any given conditions.] Unfortunately there is virtually no information which enables this to be acheived. Distinction between the cases of Figures 2b and 2c may not be too important as in both cases reattachment occurs at the shoulder so that the separated region may be defined following the ideas of Reference 1. Nevertheless the ability to distinguish between type 2b and type 2c flows would probably enable a more refined prediction to be made.

The most important requirement is to distinguish between the shoulder reattachment and flare reattachment cases. Ths size of the separated region for flare reattachment is a function of both flare angle and Mach number. In addition it is a function of Reynolds number, although the balance of this evidence is that an asymptotic state is reached at sufficiently high Reynolds numbers. It will be recalled that flare attachment is possible if the flare angle is sufficiently low (c.f. Figure 3 of Reference 1). However, although flare reattachment might occur for such a case on an infinitely long flare the natural size of the separation region will inhibit flare reattachment for sufficiently small flare heights.

In order to obtain some information on this the results of Kuehn (Reference 2) have been reanalyzed to give the distance of the separation point in front of the flare compression corner for various cases. It has been assumed that the asymptotic condition has been reached for Reynolds numbers (based on undisturbed boundary layer thickness) greater that 8.0×10^4.

These results are plotted in Figure 5, but it must be emphasized that this figure is only a tentative prediction based on an extremely small amount of information. Also shown are the geometric limits of step height corresponding to a separation angle of 17°. Thus for a given Mach number and flare angle the distance of the separation point in front of the compression corner for a flare reattachment will be as shown provided the step height is greater than the geometric limit. For step heights below the geometric limit the flow reverts to a shoulder reattachment, for which predictions may be made following Reference 1.

A further type of flow which could occur in some cases is a "pseudo-separation". For small flare angles the flare shock may not be sufficiently strong to cause actual boundary layer separation, particularly if the turbulence level before the shock is unusually high. However the interaction of the shock with the boundary layer will change the boundary layer characteristics and in particular may cause an increase in the turbulent energy relative to the reduced velocity of the mean flow. The increased turbulence will diffuse out into the free stream and will give the appearance of a separation on shadowgraph pictures of the flow. However the "separation" in this case will not tend to run forward from the shock as is usual, so that this type of flow should only cause confusion if the shock has been displaced from its normal position in the compression corner by some other effect. The conditions required to produce this type of flow are somewhat unusual and will only be occasionally encountered. But this possibility should not be overlooked.

Conclusions

It has been shown that the separations of a supersonic turbulent boundary layer induced by a forward facing flare or step may be divided into two classes depending on "flare reattachment" or "shoulder reattachment" respectively. This classification was made in Reference 1 although it was described somewhat differently. The flare reattachment case corresponds to the flows studied in detail by Kuehn in Reference 2, and a tentative method for their prediction has been proposed.

The shoulder reattachment cases may be further divided into two groups. Reattachment occurs via a shock near the shoulder for one group, typically the flows over forward facing 90° steps. For the more moderate flare angles usually encountered on Saturn type vehicles no shock is visible, and reattachment occurs either via the shoulder expansion wave or through a gradual pressure rise up the flare. The exact mechanism of reattachment in this case is uncertain.

The possibility of "pseudo-separation" is also pointed out. Though the shock wave may not be sufficient to cause a reverse flow i.e. true separation, the increase in turbulence level after passing through the shock may give rise to an expanding turbulent region which will appear like a separation in shodowgraph pictures. However it is anticipated that this type of flow will be rare.

Unfortunately very little information is available relevant to the problem of predicting the flow type for any given configuration. Some tentative ideas have been put forward here but it is suggested that a short series of experiments would yield much useful information. The experiments would consist of shadowgraph photography of a sufficiently broad range of configurations and Mach numbers to provide reasonably complete coverage of the various flow types. As well as revealing the overall characteristics of the flow, analysis of the shock wave angles would provide information or the effective displacement angles of the separation region. This could be coupled with oil flow visualization of the surface characteristics which would provide independent measurements of the separation and, to a lesser extent, the reattachment points. Such experiments could be carried out in MSFC tunnels. This would provide very valuable information on the various flow types of separated flow that occur, and would thus be of major value in the preparation of a prediction technique.

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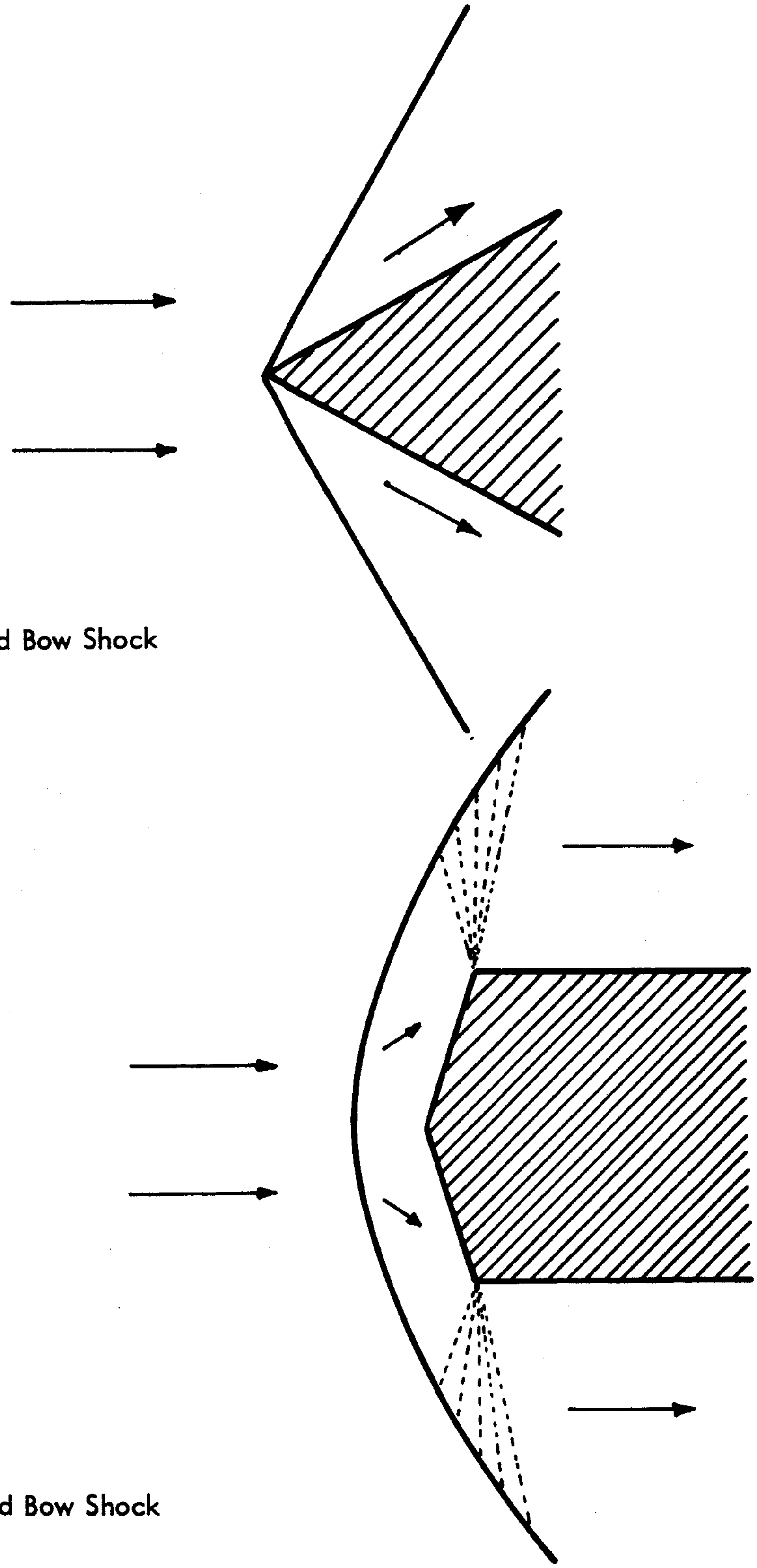

1a) Attached Bow Shock

1b) Detached Bow Shock

Figure 1: Supersonic Flow Fields Around a Blunt Body

Figure 1a: Initial Stage of Vortex Break-
down on a Delta Wing

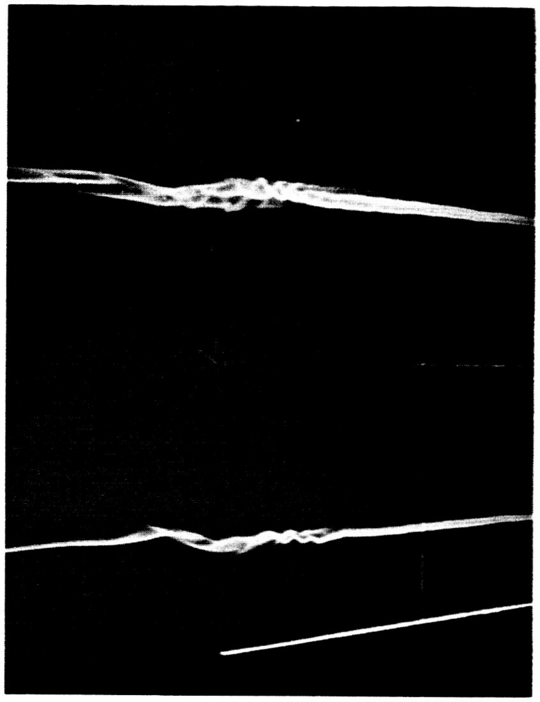

Figure 1b: Later Stage of Vortex Break-
down.

These pictures taken from Reference 15

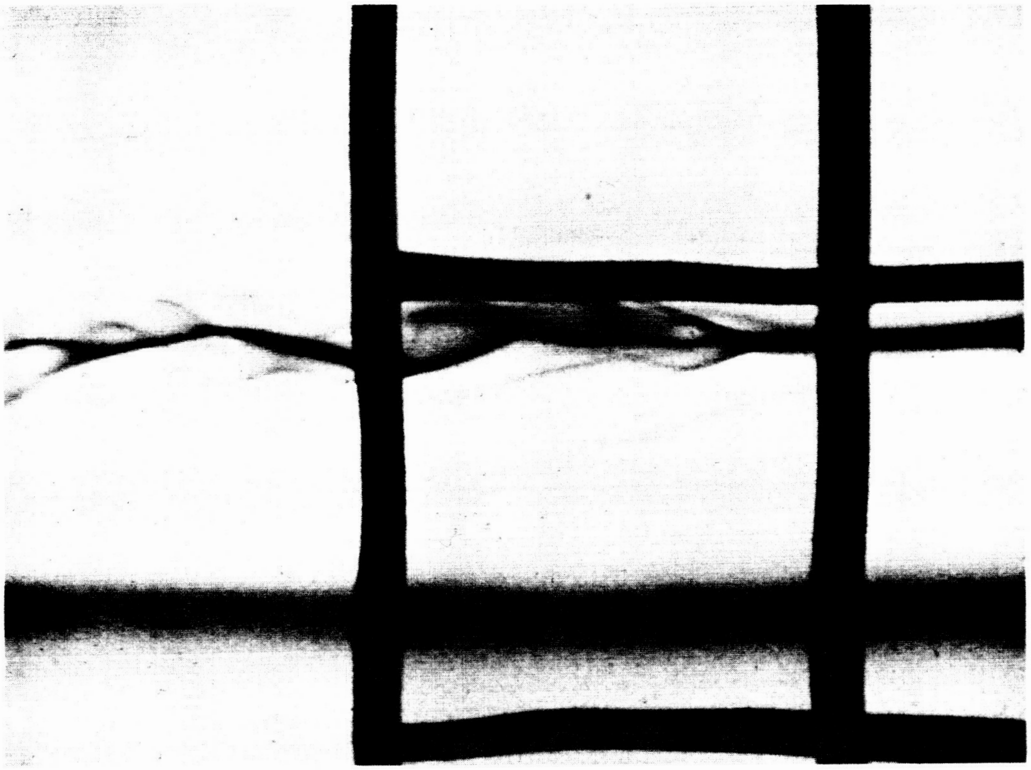

Figure 2a: Initial Form of Disturbed Dye

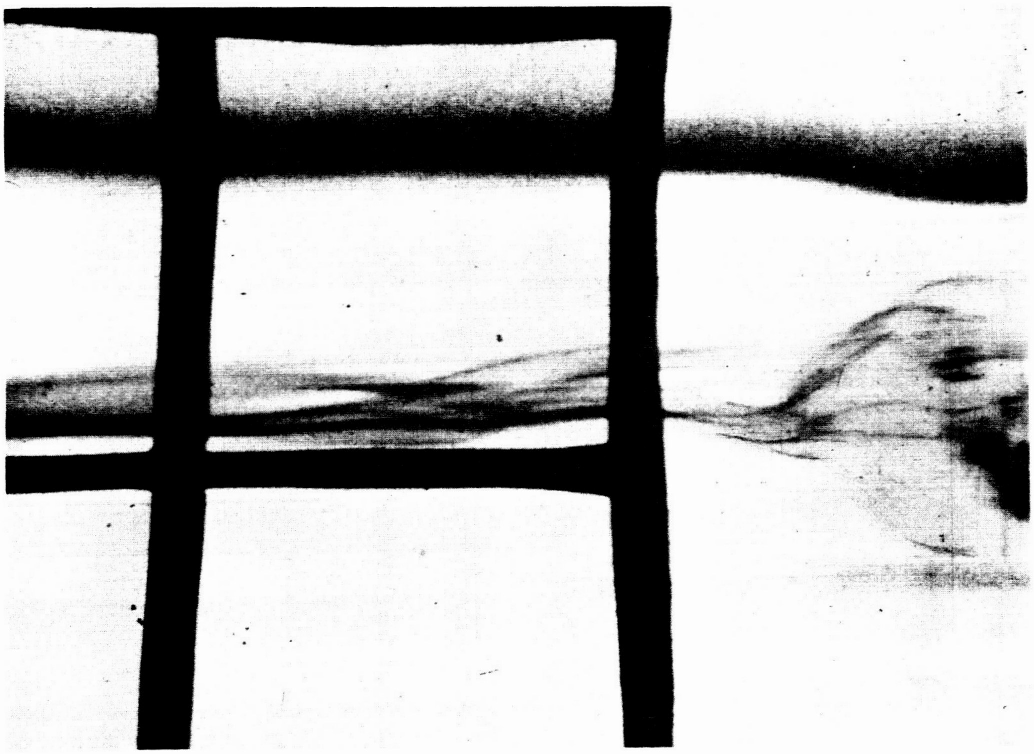

Figure 2b: Later Form of Disturbed Dye

These pictures taken from Reference 10. Figure 2b has been retouched to facilitate reproduction, but all features shown were apparent on the original 16 mm color motion picture.

Figure 2: Form of Disturbed Dye Streaks During Later Stages of Transition from Laminar to Turbulent Flow in a Boundary Layer.

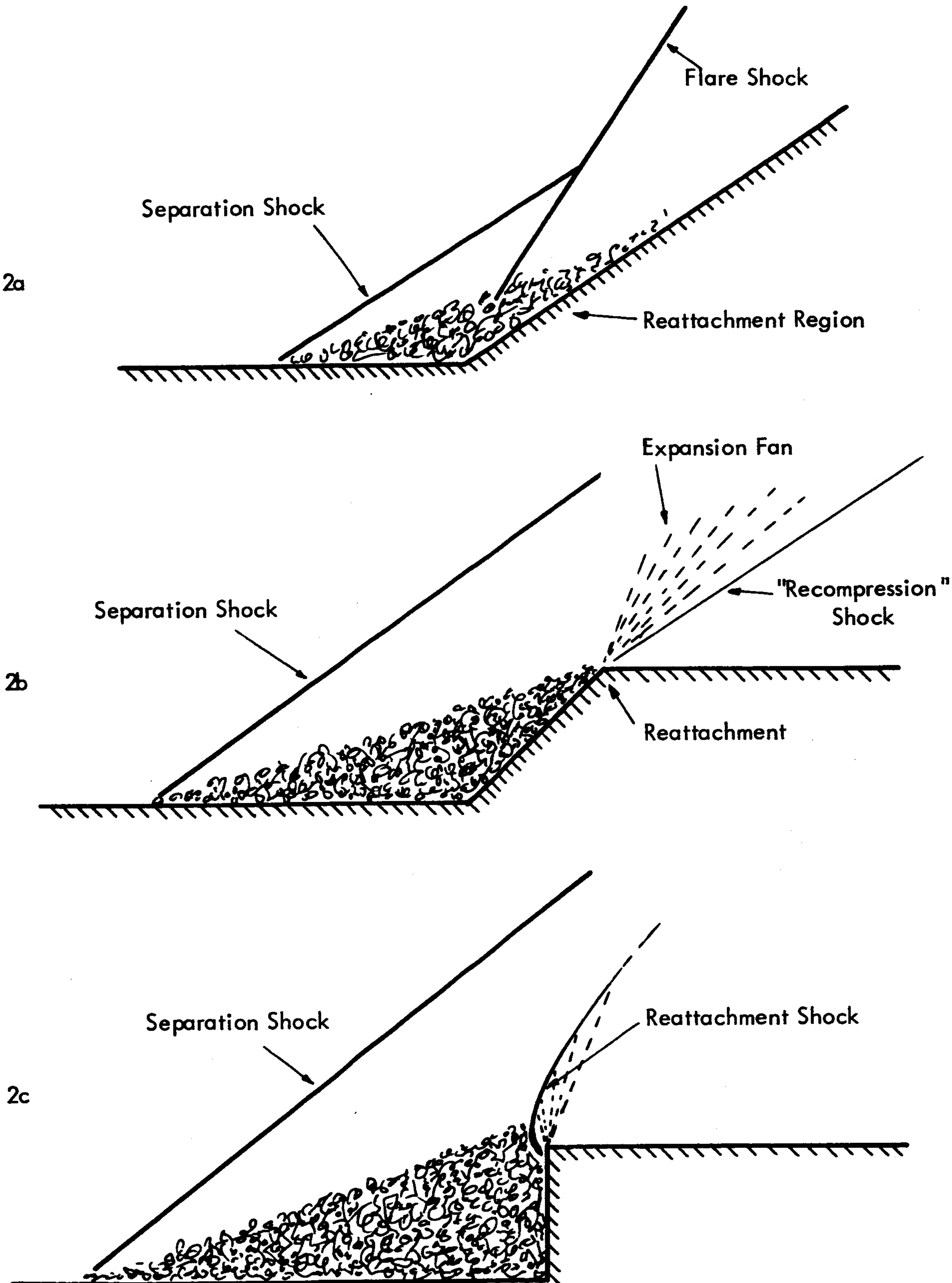

Figure 2a

Figure 2b

Figure 2c

Figure 2: Types of Turbulent Supersonic Separated Flow

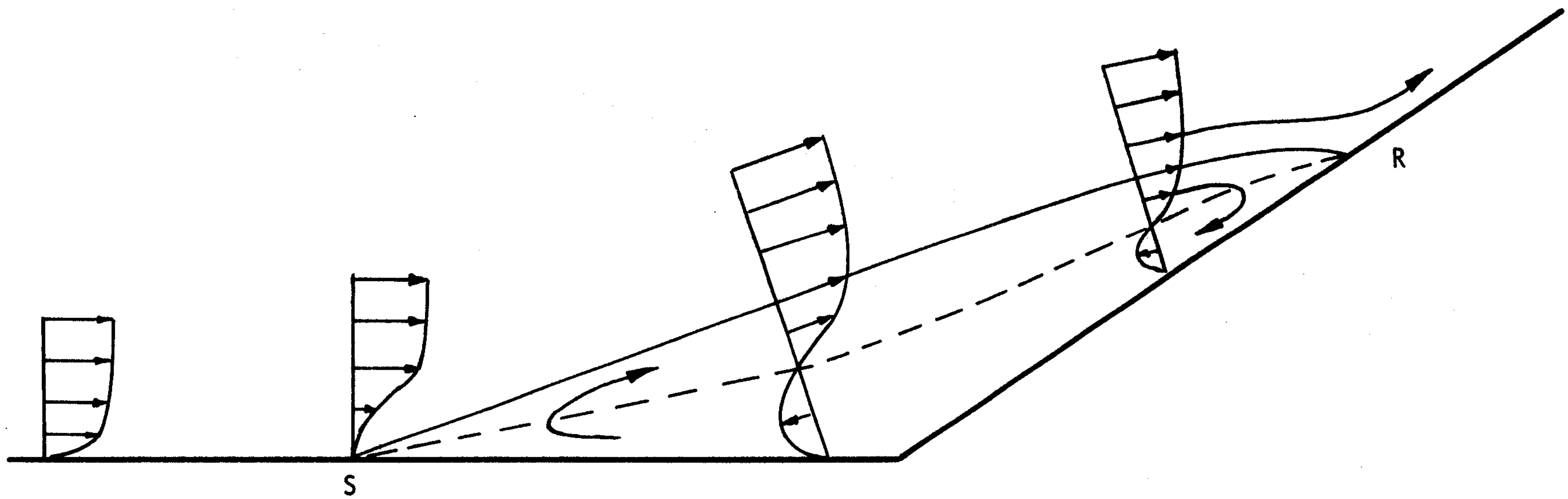

Figure 3: Flow Patterns in a Model Separation and Reattachment

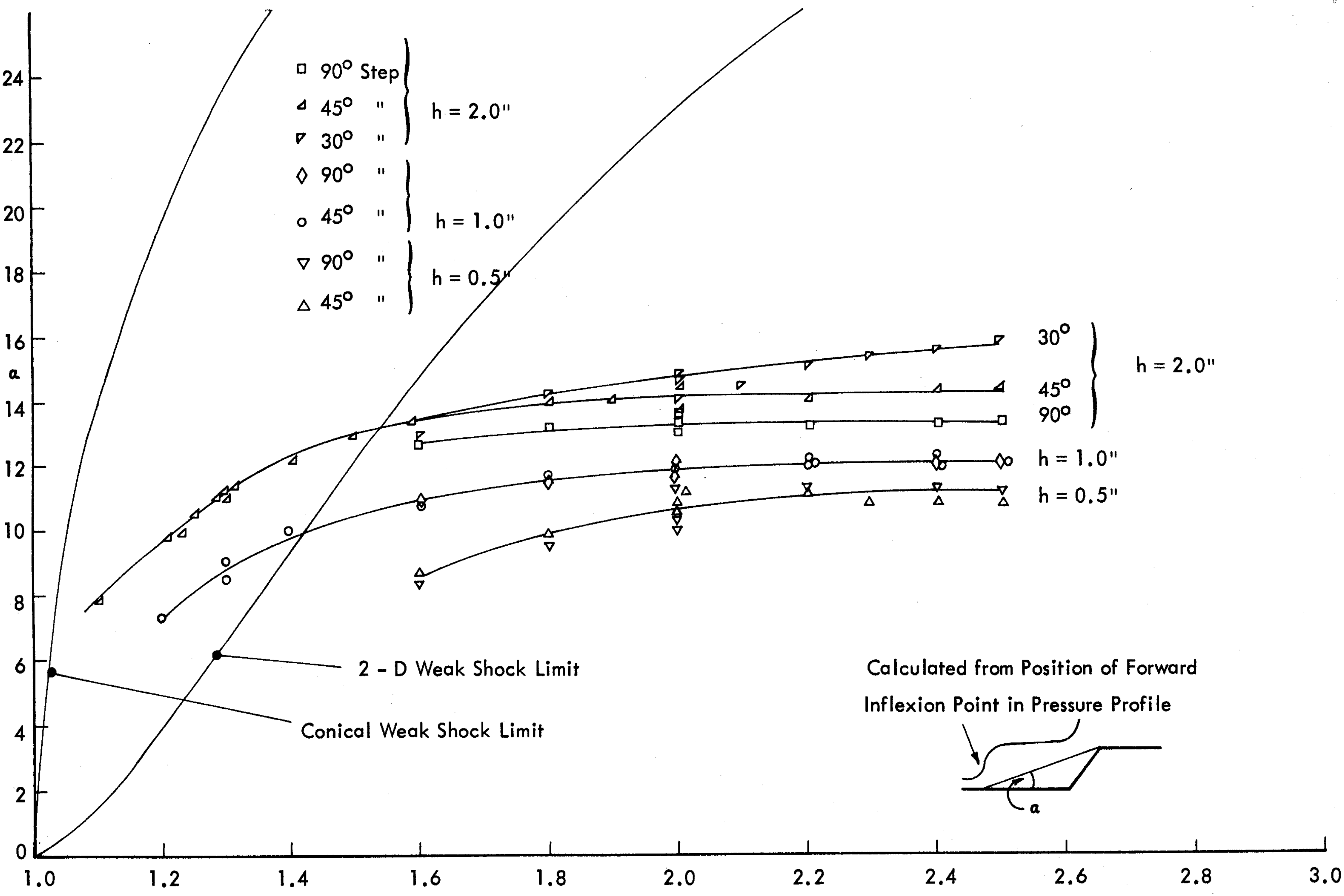

Figure 4: Separation Angle vs Mach No. From Ames Data

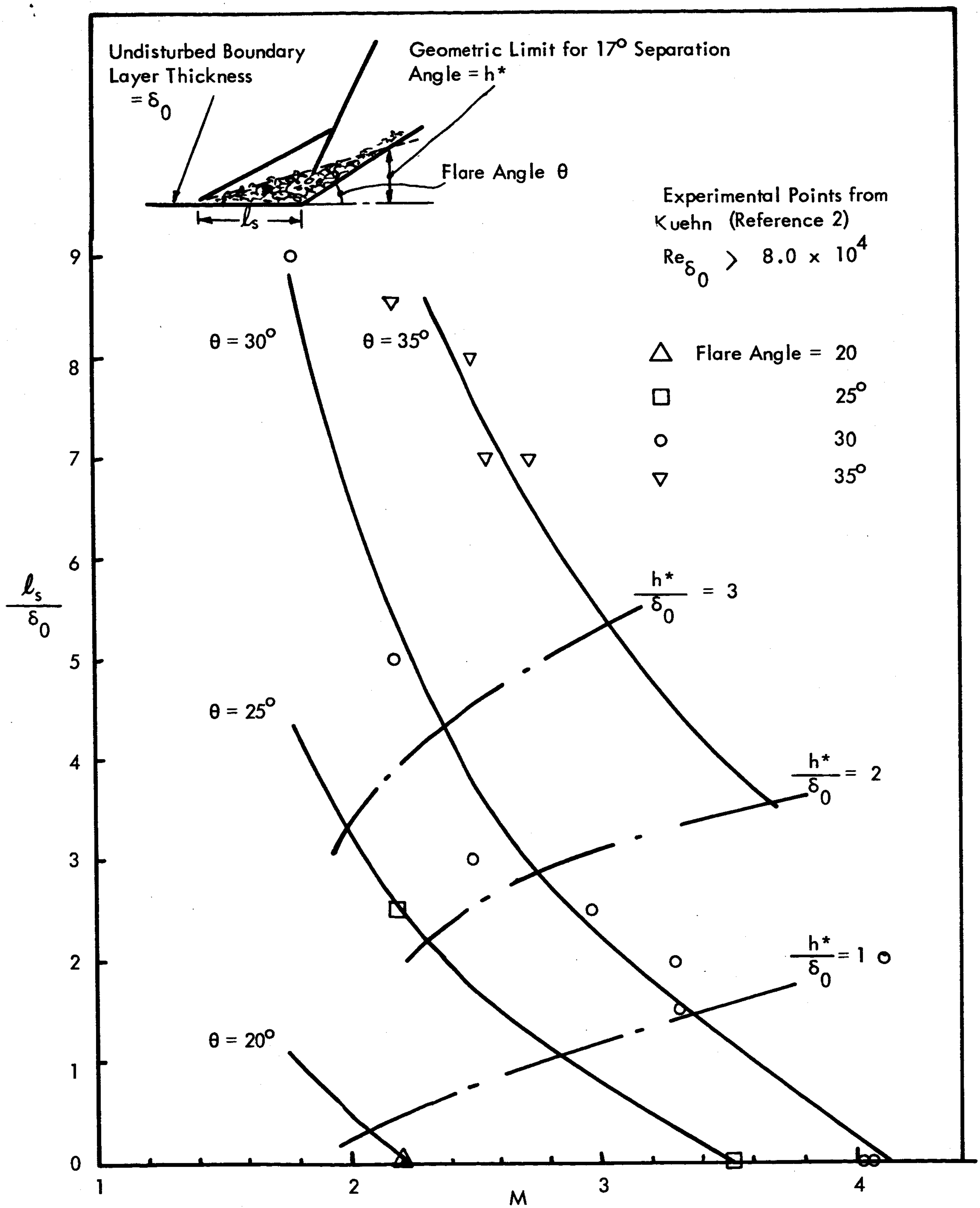

Figure 5: Separation Length vs Mach Number and Flare Angle for Flare Reattachment Cases

APPENDIX B

TRANSITION AND VORTEX BREAKDOWN

Summary - It is pointed out that the later stages of transition from laminar to turbulent flow in a boundary layer bear a strong resemblance to the "vortex breakdown" observed in separated flow over slender wings. (2)

Experimental approaches to the problem of transition have followed two rather different paths. The first approach is a natural extension of the two dimensional stability analyses of Tollmein and Schlicting which were confirmed in the original experimental work of Schubauer and Skramstad. This work relies on a study of the flow arising after introduction of a two-dimensional disturbance into the boundary layer, and has led to a detailed knowledge of the initial stages of transition for this case c.f. References 1-6. The most detailed observations are given by Hama and Nutant (Reference 1). It is found that the two dimensional disturbance amplifies in a non-uniform manner and turns into a series of hairpin vortices with axes parallel to the free stream. The vortex then undergoes a "complicated tangling" which results in turbulence.

The second approach to the problem has arisen from attempts to investigate a "natural" transition free from any deliberate attempts to disturb the fluid, (c.f. References 7-10). For this case it has been found that the turbulence appears in "spots". These spots are random in space and time, but expand during their convection downstream until sufficiently far downstream the whole flow is turbulent. The turbulent flow for this case is usually visualized by the injection of a thin layer of dye at the wall, and it is found that the dye patterns in the laminar region even before the onset of turbulence have formed into streaks. The dye streaks during transition adopt an increasingly disturbed motion until eventually the dye pattern erupts away from the wall as a small eddy. This eruption was first observed for fully turbulent flow by Einstein and Li, (Reference 11), but seems also to be a characteristic of the transition process.

The dye patterns for this natural transition case are streaks in the stream direction with weak rotation. This form is nearer to the Taylor - Gortler instability pattern than to the Tollmein-Schlicting case and does raise a question as to the actual instability mechanism which causes real natural transition. However the flow pattern at an intermediate stage of the transition process in both the natural transition case and the two dimensional disturbance case is a row of weak vortices with their axes aligned with the stream. It is the development of this model which bears an interesting resemblance to the vortex breakdown phenomenon.

Vortex breakdown is the term applied to the sudden expansion of the leading edge vortices that occur in the separated flow over slender wings. The effect seems to have been discovered independently by a number of workers, and has subsequently been the result of much experimental investigation (References 12-15). Reference 13 by Lambourne and Bryer gives a particularly complete account. It is found that this breakdown occurs at a definite wing station and will move forward with increase in incidence or decrease in leading edge sweep. The parameter which has the most direct affect on the breakdown position appears to be the streamwise pressure gradient.

Theoretical studies of vortex breakdown have also been pursued. Initially it was thought that the breakdown was due to an instability and a number of papers have appeared explaining this avenue with increasing sophistication (References 16, 17, 18). More recently, however, Brooke Benjamin has suggested (Reference 19) that the phenomenon is the change from one conjugate flow to another, akin to a shock wave, or with more similarity to the "hydraulic jump" effect. However no author has yet been able to predict the occurrence of vortex breakdown.

The main interest in the present note is in the results reported in Reference 15. In these experiments a delta wing was oscillated in pitch, and it was found that this caused the leading edge vortices to undergo breakdown. Thus it was possible to study the mechanisms occuring during the breakdown process rather than having to observe an already established breakdown as was the case during static tests. The experiments were carried out in a water tunnel so that the flow could be visualized by injecting fluorescent dye into the vortex cores. The results shown in Figure 1 were obtained. Figure 1a shows how the vortex core which was hitherto smooth and straight has developed into helices. This is clearly the result of a non-aisymmetric instability and at a later time the flow develops into the form shown in Figure 1b. The difference between the left hand "thistle" and right hand "helical" formations of Figure 1b may be noted.

It is found that breakdown will occur as either of these types but that each can reform into the other. Further details of the experiments may be found in Reference 15.

It will be recalled that at an intermediate stage in the transition process the wall dye pattern resemblies a number of weak vortices in the stream direction. The subsequent development of these vortices is shown in Figure 2. The photographs in Figure 2 have been taken from a motion picture made by Meyer and Kline (References 9 and 10), and show opaque dye patterns in the boundary layer of water channel. The heavy black lines are a reference grid distorted by the water surface.

Figure 2a shows the initial form of the disturbed dye and exibits a clear similarity to the initial form of the vortex breakdown shown in Figure 1a. Figure 2b shows a later development of dye pattern during transition and it can be seen how this again resembles the later development of vortex breakdown shown in Figure 1b. For reference, Figure 1 corresponds to flow developments 0.27 seconds apart in a flow with a free stream velocity of 0.75 f.p.s. while Figure 2 gives flow developments 0.78 seconds apart in a flow with a free stream velocity of 1.0 f.p.s.

These two figures show a very interesting similarity between vortex breakdown and the later stages of transition. The pictures do not, of course, represent a proof, but do strongly suggest that the flow mechanisms for these two cases may be the same.

If these flows are similar then an improved physical understanding of the later stages of transition is possible, and the results from investigation of one flow maybe used to advantage in interpretation of the other. For instance, the observed sensitivity of vortex breakdown to pressure gradient has obvious parallels in the case of transition. It is possible that a single vortex could be used as an easily controlled model flow for the later stages of transition. In addition, some of the theoretical work which has been aimed at an understanding of transition has a direct application to vortex breakdown. In Reference 20 Weske and Rankin show the existence of instability modes for a vortex which are very similar to those shown in Figure 1a. The work of Hama (References 21, 22) has shown how a line vortex is stable to small amplitude sinusoidal disturbances, but not to those of large amplitude or with non-sinusoidal form. This may provide an explanation of the failure of stability analyses for the vortex breakdown case.

In fact this also provides some explanation of the failure of theories attempting to find Taylor-Gortler type instabilities on a flat surface.

This idea also has interesting applications to the case of the fully developed turbulent boundary layer. Runstadler, Kline and Reynolds (Reference 23) have shown how the flow field in the laminar sublayer of fully developed turbulence is very similar to that observed during the transition process. Thus, this transition model may have application in understanding the eruption processes in the laminar sublayer. In a report enclosed with the monthly progress report for February (Reference 24) it was shown how this laminar sublayer eruption could well be the actual cause of the major part of the surface pressure fluctuations observed beneath a turbulent boundary layer. In context with this it is interesting to note that major increases in surface pressure fluctuations have been observed beneath vortex breakdowns over delta wings (Reference 25). See also Appendix C of this progress Report.

Thus the resemblance between these two types of flow does lead to some interesting suggestions. However the differences between these flows should not be overlooked. Firstly, the major difference in strength is apparent. Secondly, the transition vortices occur in a region of high mean shear. Thirdly, the vortex core in the separated flow has higher axial velocities than the surrounding flow whereas the dye flow velocities in the transition case are generally less than the local surrounding flow. However, in spite of these differences the flow mechanism for each case may still be the same, and certainly the similarities apparent in Figures 1 and 2 suggest that further work in correlating these two flows would be desirable.

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APPENDIX C

Addendum to: Wyle Research Staff Report 65-2 Pressure Fluctuations in Turbulent Boundary Layers (Submitted with February 1965 Progress Report).

A paper by Kovasznay, Komoda and Vasudeva, (Reference 27) provides further independent exidence supporting the hypothesis that the wall pressure fluctuations are the result of laminar sublayer eruption. Their work was a study of the transition from laminar to turbulent flow in a boundary layer. The work of Runstadler, Kline and Reynolds (Reference 21 of the Report) shows how the laminar sublayer in a fully developed turbulent flow has similarities to the flows occurring during transition, so that the details of the flow patterns observed during the transition process may taken as representative of those occurring near the wall in the turbulent boundary layer. Kovasznay et al calculated the wall pressure effects of a flow development corresponding to an "eruption" and find that it can cause pressure pulses of the order of a few percent of the free stream total head. This is sufficient to account for the fluctuating pressures actually observed beneath a turbulent boundary layer and provides further evidence in support of the hypothesis.

Additional Reference

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